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PROJECT SCHEDULING TECHNIQUES AT THE VLAAMSE MAATSCHAPPIJ VOOR WATERVOORZIENING

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ABSTRACT

The scheduling of activities over time has gained increasing attention with the development of the *Critical Path Method* (*CPM*) and the *Program Evaluation and Review Technique* (*PERT*). Since then, a large amount of solution procedures for a wide range of problem types have been proposed in the literature. Many of these procedures, however, are not able to solve real life problems.

In this paper we describe a capacity expansion project at a water production centre (WPC) of the *Vlaamse Maatschappij voor Watervoorziening* (VMW) in Belgium. This project aims at expanding the production capacity of pure water. We show that scheduling the project with certain techniques will improve the financial status of the project. We illustrate this statement with different schedules.

Keywords: *Real-life problem; Net present value.*

1 Introduction

The *Vlaamse Maatschappij voor Watervoorziening* (VMW) is a Flemish water distribution company, which covers approximately 50 percent of Flanders, located in the northern region of Belgium. The VMW services 2.5 million customers with a pipeline network of 27,000 km and a yearly production of 140 billion litres of water.

In this paper we focus on a project at the water production centre (*WPC*) of Kluizen, which belongs to the VMW. This centre produces and delivers water by transforming surface water into drinkable water and distributing it towards the customers. Therefore, surface water is taken from the area (with a total surface of ±120 km^2) around the *WPC* and is stored in two open reservoirs (*spaarbekkens*, *SB*1 and *SB*2) of a total capacity of 11,000,000 m^3. From this point on, a number of different steps are performed in order to purge the water and make it drinkable. In figure 1 we show the different steps of this production process without going into detail.

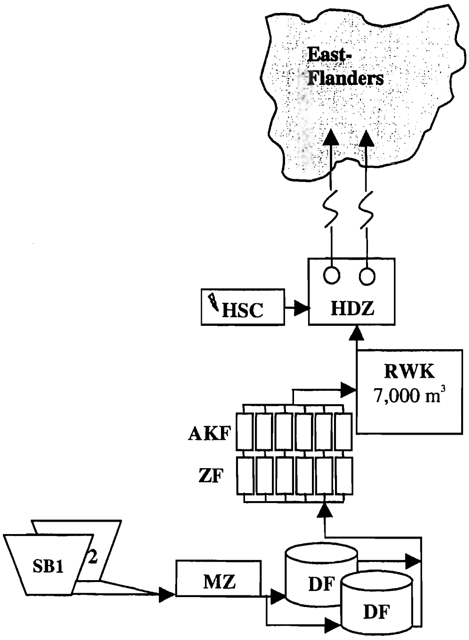

Figure 1. *Graphical scheme of the production process at the WPC of Kluizen*

The filtering of the surface water consists of a number of filtering steps. These are, in order of appearance, the micro sieving (*microzeef*, *MZ*), the decantation filtering (*decantatiefilter*, *DF*), the filtering with sand (*zandfilter*, *ZF*) and the carbon filtering (*actief koolfilter*, *AKF*). Chemical products are added at various points during this process (e.g. H_2SO_4, $AlCl_3$, NaOH, NaOCl). At the end of this water treatment process, the pure water is stored in a reservoir with treated water (*reinwaterkelder*, *RWK*) which forms a buffer between the treatment and the pumping phases. During the pumping phases, a number of pumps which are located in a high pressure room (*hogedrukzaal*, *HDZ*) disperse the water to the different regions in East Flanders. This *HDZ* is fed with energy coming from the high voltage cabine (*hoogspanningscabine*, *HSC*).

The storage capacity of the *RWK* amounts to 7.000 m^3 while the daily demand of pure water equals 30,000 m^3 or more (at peak moments, it amounts to 40,000 m^3/day). For this reason, an extension of the storage capacity of pure water is needed (referred to as subproject 1 in the sequel of this paper). Moreover, forecasts of the daily demand indicate an increase to 59,000 m^3/day in 2005 and 65,000 m^3/day in 2013. Since the existing production centre (as depicted in figure 1) works nowadays at almost 100% capacity, an extension is needed. This observation has led to the idea of building a new production centre with a much higher capacity (referred to as subproject 2). In section 2 we describe these two subprojects in more detail.

2 Description of the project

In this section we briefly describe the two subprojects of the project at the WPC Kluizen, i.e. subproject 1, '*an extension of the storage capacity of treated water*' and subproject 2, '*an increase of the production capacity to* 70,000 *m^3/day*'. The first subproject, as described in section 2.1, consists of an increase of the storage capacity by building two extra reservoirs for treated water (*RWK*) which serve as buffers for pure water between the treatment and the pumping phases. In doing so, the *WPC* will be able to meet the daily demand of the customer much easier. It does, however, not lead to the desired increase in the production capacity. In a second subproject, which is described in section 2.2, the construction of the new production centre must guarantee the desired production capacity of 70,000 m^3/day.

2.1 Subproject 1: Extension of the storage capacity of treated water

This first subproject consists of two steps, i.e. the building of the two reservoirs for treated water (*RWK*) at the production plant itself and the additional activities outside the production plant.

2.1.1 Activities at the production plant itself

In order to increase the storage capacity of pure water, two new reservoirs for treated water (denoted by *RWK*1 and *RWK*2) have to be built, each with a capacity of 15,000 m^3. Pumps in a new high pressure room (*HDZ*') will assure the circulation of the pure water towards the customer, while the energy supply has to come from a new high voltage cabine (*HSC*'). The existing pumps located at the *HDZ* will be modified (in fact, they will be replaced by pumps with middle pressure capacity, *middendrukzaal*, *MDZ*) in order to assure the flow of water towards the new reservoirs. Constructing pipes between these installations will complete this first step of subproject 1. Figure 2 gives a graphical representation of this first extension. Due to the new reservoirs for treated water *RWK*1 and *RWK*2, it will be much easier to satisfy peak moments in demand. The newly established installation will still not be able to produce much more than 30,000 m^3/day.

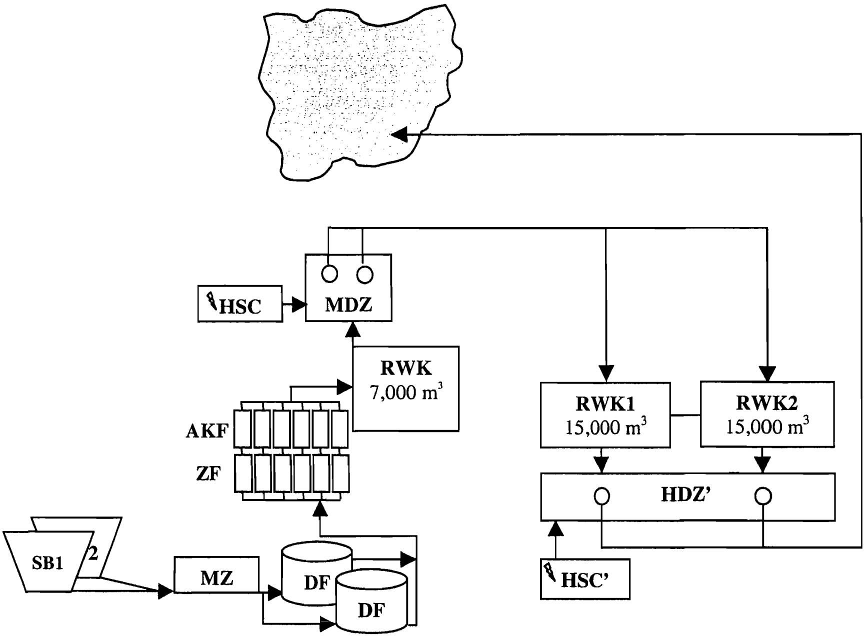

Figure 2. *Graphical scheme of the production process at the WPC of Kluizen and the new storage extensions (RWK1, RWK2, HDZ' and HSC')*

A list of the detailed activities of these steps is depicted in Table 1 of the appendix. Each activity has an ID number and a task name. The duration and the cost of each activity are also given in this table. Figure 3 gives a network representation of the different tasks of this subproject. Notice that the precedence relations between the activities are of the finish-start type (*FS*) with a time-lag of zero, unless it is otherwise indicated at the bottom of the table. The total estimated cost of this step amounts to 7,483,905.51 € or 301,900,000 BEF (1 € = 40.3399 BEF).

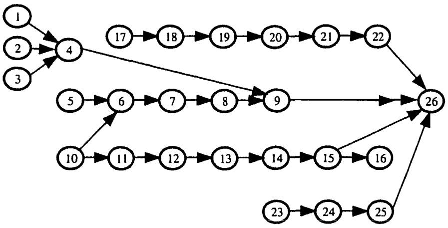

Figure 3. *Network representation of the work completed at the production plant WPC Kluizen*

2.1.2 Activities outside the production plant

The activities outside the production plant mainly focus on an optimal supply of the pure water to the customer. Therefore, a new pipeline has to be constructed from the *WPC* Kluizen to its customers (towns in the northern region of Flanders such as Eeklo and Waarschoot). Moreover, at some regions, *WPC* Kluizen is obliged to deliver a certain amount of water to the *TMVW* (*Tussengemeentelijke Maatschappij Voor Watervoorziening*) while at other regions (e.g. Zelzate) the delivery is vice versa (*WPC* Kluizen receives an amount of water). The main steps of this subproject, shown in figure 4, are:

- *(i)* the construction of a new pipeline between Kluizen and Eeklo,
- *(ii)* the delivery of water to the *TMVW*, (i.e. building a measuring station and fitting it in the existing communication system),
- *(iii)* the construction of a pumpstation (in order to increase the pressure of the water, denoted by the symbol ▱) at Zelzate,
- *(iv)* the construction of a pumpstation (in order to increase the pressure of the water which supplies a water tower in Eeklo,
- *(v)* the construction of a pumpstation (in order to increase the pressure of the water) in Waarschoot.

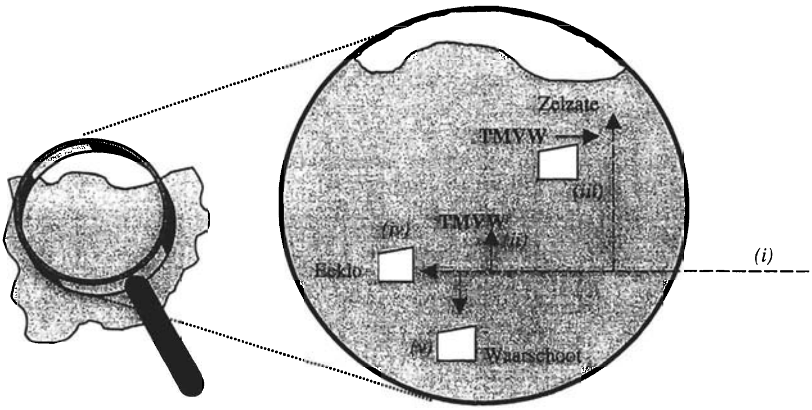

Figure 4. *Graphical scheme of the second step of subproject* 1 *outside the production plant*

As before, a list of the detailed activities of these steps is depicted in Table 2 of the appendix. Figure 5 gives a network representation of the different tasks of the second step of subproject 1. It has a total estimated cost of 5,032,238.55 € or 203,000,000 BEF.

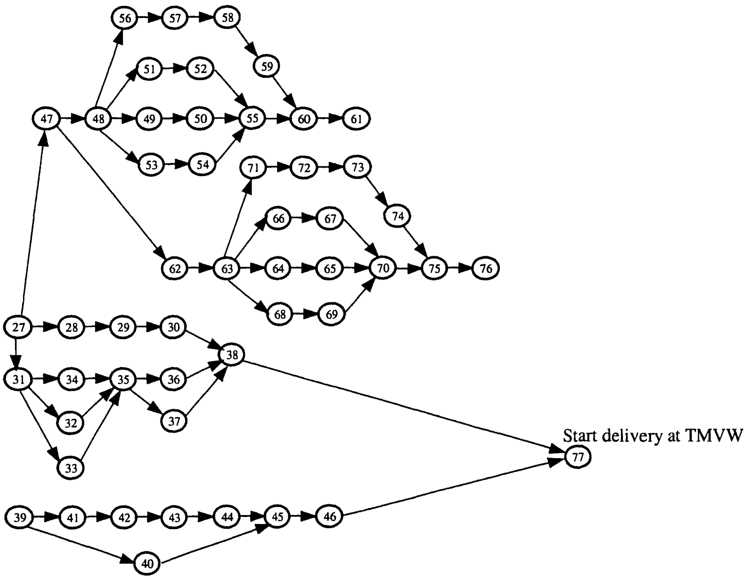

Figure 5. *Network representation of the work completed outside the production plant WPC Kluizen*

2.2 Subproject 2: Increase of the production capacity

The construction of the new production centre with a desired production capacity of 70,000 m^3/day is a capital-intensive project with a total estimated cost of ±13,262,303.58 € or 535,000,000 BEF. It consists mainly of three steps, i.e. building the carbon filters (*actief koolfilters, AKF*), establishing an alternative system for the decantation filtering and the treatment of waste.

(*i*) In a first step, 12 new carbon filters (denoted by *AKF'* in figure 6) will be built in two phases. In a first phase, 3 carbon filters will be built, while in a second phase the remaining 9 carbon filters will be installed.

(*ii*) In a second step, an alternative technique for the rather "old-fashioned" decantation filtering step (see figure 1) has to be selected. The two considered possibilities are[1]:

1. **Membrane processes** (*membraanfilter, MF*) employ a semi-permeable (selective) membrane and a driving force (pressure, concentration, etc.) across the membrane to separate target constituents from a feed liquid. Water passes through the membrane, forming a treated water stream (permeate) and leaving behind the other constituents in a concentrate. Different types of membrane processes can remove dissolved and colloidal constituents in the size range of 0.0001 to 1 micron. The commercially available membrane processes include micro-filtration, ultra-filtration,

[1] The definitions of the membrane processes and the air flotation techniques are downloaded from http://www.interduct.tudelft.nl/

reverse osmosis, membrane electrolysis, and diffusion dialysis. The technologies operate differently, and each is best suited for specific applications. They are all useful for separation of molecular mixtures.

2. **Air flotation techniques** (*flotatiefilter*, *FF*) are used to remove insoluble contaminants from a solvent. The removal is based on the adhesion of dissolved air at the contaminants, after which it will come to the surface of the liquid.

The total cost of this step amounts to 7,560,752.50 € or 305,000,000 BEF for the first alternative and 5,825,497.82 € or 235,000,000 BEF for the second alternative. In the sequel of this paper, we restrict ourselves to the first alternative. Similar results with respect to the proposed schedules of section 3 will be obtained in the case of the second alternative.

(*iii*) The third step deals with the sludge treatment (*afvalverwerking*, *AW*) and has a total estimated cost of 991,574.09 € or 40,000,000 BEF. The sludge is disposed of in containers after being thickened and desiccated.

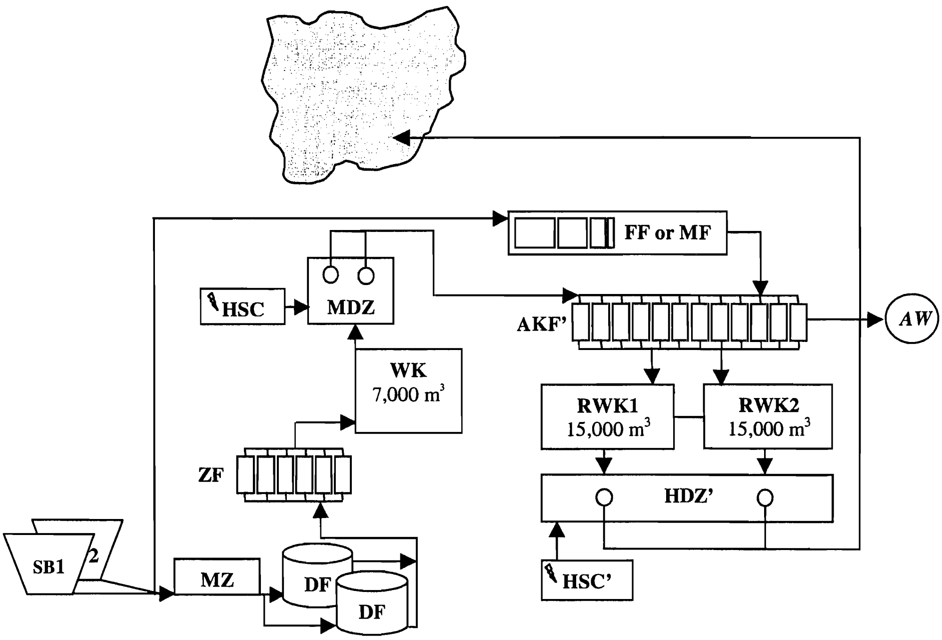

Figure 6. *Graphical scheme of subproject* 2 *'increase in capacity'*

The results of subproject 2 are depicted in figure 6. This figure reveals that the original reservoir for treated water (*RWK*) with a capacity of 7,000 m^3 now serves as a reservoir for non-treated water (waterkelder, *WK*) since the *AKF* is removed from the picture. Consequently, the water stored in this *WK* still has to pass the *AKF'* step before being stored in *RWK*1 or *RWK*2. In the long run, the new water production centre must replace the old production centre of figure 1. When this is the case, the non-treated water will flow directly from $SB1$ and $SB2$ to the first filtering step, i.e. step *FF* or *MF*. A detailed activity list of these steps is depicted in Table 3 of the appendix. Figure 7 gives a network representation of the different tasks of this project.

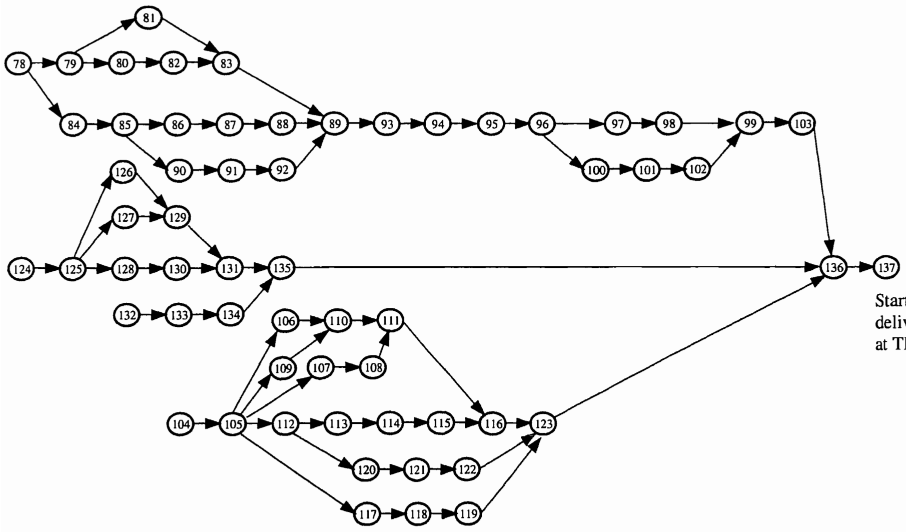

Figure 7. *Network representation of the three steps to increase the production capacity*

3 Analysis of the project

3.1 Features of the project

The project under study is the subject of a widely discussed topic in the project scheduling literature. It involves the scheduling of project activities in order to maximize the net present value (*npv*) of the project in the absence of resource constraints. This observation finds its motivation by the following statement by Herroelen et al. (1997):

> *"When the **financial aspects** of project management are taken into consideration, there is a decided preference for the **maximization of the net present value** of the project as the more appropriate objective, and this preference **increases with the project duration**"*

Since the project at hand is a very capital-intensive project (total estimated cost exceeds the value of 25,000,000 €) with a makespan of approximately 7 years, the maximization of the net present value seems the appropriate objective function. This problem is classified in the project scheduling literature as the max-*npv* problem and can be formulated as follows:

$$\text{Maximize} \sum_{i=1}^{137} c_i e^{-\alpha(s_i+d_i)} \qquad [1]$$

Subject to

$$s_i + l_{ij} \leq s_j \qquad \forall (i,j) \in A \qquad [2]$$

$$s_{137} \leq 362 \qquad [3]$$

$$s_0 = 0 \qquad [4]$$

in which the variables d_i, c_i, s_i and f_i denote the duration, the cost, the starting time and the completion time, respectively, of an activity i. The set of arcs, A, represents the precedence constraints of a project (with a time-lag l_{ij}) while α represents the discount rate. We have already noticed in section 2 that the minimal time-lags of the project equals zero ($FS_{i,j}^{\min} = 0$ and consequently, $l_{ij} = d_i$) unless otherwise indicated. Extra arcs are added to the project for activities with ready times $\rho_i \neq 0$, i.e. $FS_{0,i}^{\min} = \rho_i$ or $l_{0i} = \rho_i$. The objective function in Eq. 1 maximizes the net present value by compounding the value of each activity towards the beginning of the project as follows: $c_i e^{-\alpha(s_i+d_i)}$ = $c_i e^{-\alpha f_i}$. The constraint set given in Eq. 2 maintains the precedence relations with time-lag l_{ij} among the activities. Eq. 3 limits the project duration to the project deadline of 362 weeks (in fact, the project started at the end of January, 1999 and has to be finished at the beginning of 2006) and Eq. 4 forces the dummy start activity to start at time zero.

For more information and a solution procedure for the max-*npv* problem, we refer the reader to Vanhoucke et al. (1999). In Vanhoucke et al. (2000), this solution procedure is extended to the case where both minimal and maximal time-lags are involved.

In figure 8 we display an activity-on-the-node network representation of the entire project. Remark that we have coloured the nodes with a cost $c_i < 0$ in black. Grey nodes represent activities which are required to finish as early as possible. Remark that these activities always present an end activity of a subset of connected activities which has to finish as soon as possible.

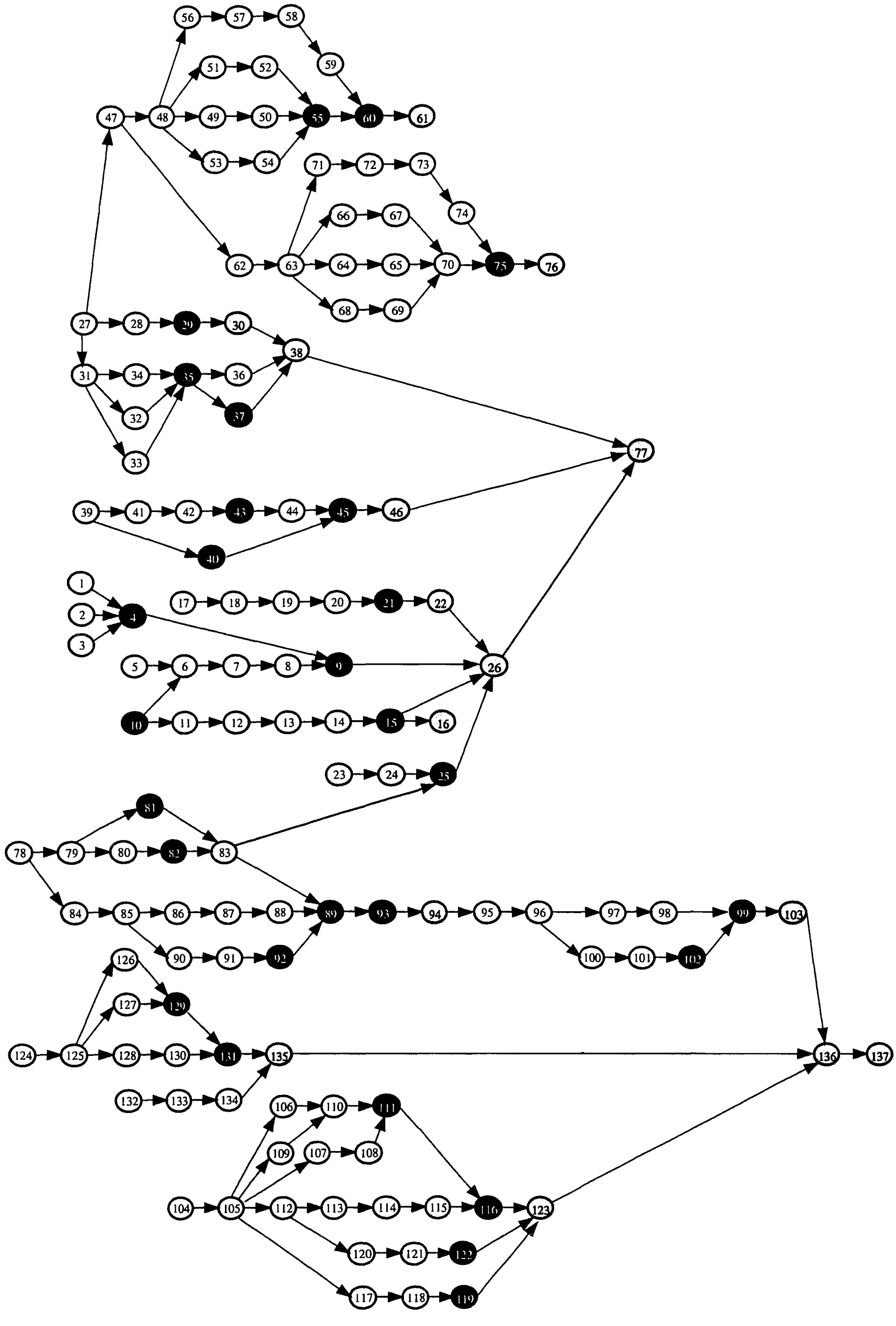

Figure 8. *Network representation of the project*

In section 3.2, we schedule the activities as soon as possible and calculate the net present value. In section 3.3 we present some modifications to the schedule in order to increase the net present value of the project. Section 3.4 proposes a robust schedule which combines the advantages of both schedules.

3.2 Earliest start schedule

Figures 9 and 10 display a Gantt chart which proposes a schedule in which all activities are performed as soon as possible (i.e. an earliest start schedule (*ESS*)). The black bars represent the schedule of each activity in time while the grey bars are used to represent the slack of each activity. This activity slack is calculated under the assumption that the grey activities of figure 8 still have to be performed as soon as possible. Consequently, an activity with label 'as soon as possible' has a slack of zero. The activity numbers with a value $c_i < 0$ are highlighted in black.

This schedule has a net present value of -21,398,569 € (we have used a weekly discount rate α = 0.0938 % which corresponds to an annual rate of approximately 5%). The schedule has the advantage that there are still quite a number of activities that can be shifted forward in time (towards the deadline) without violating the project deadline. The length of the shift is represented by the grey bars of figures 9 and 10. This means that, when something unexpected happens (and it always does) which causes delays in the activities, there is a chance that the project deadline of 362 weeks (at the beginning of 2006) will still be met. This is, of course, not true for delays in activities scheduled on the critical path (given the project deadline of 362 weeks).

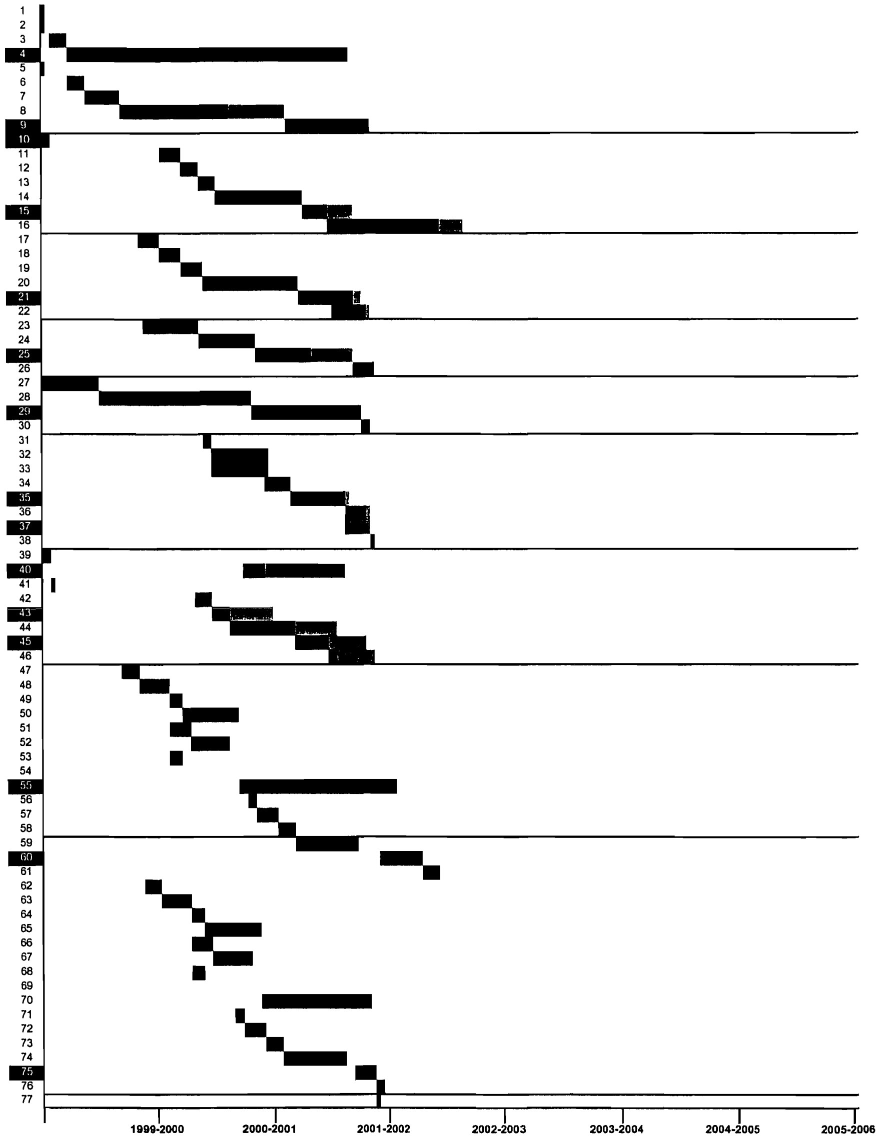

Figure 9. *Earliest start Gantt chart of subproject* 1

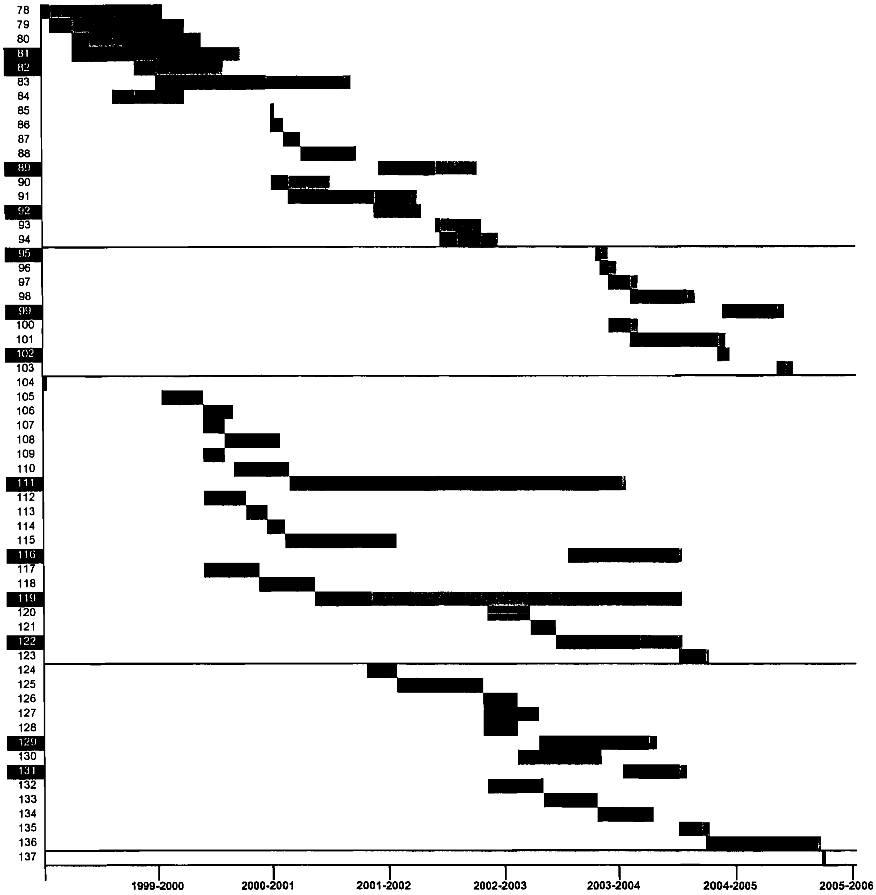

Figure 10. *Earliest start Gantt chart of subproject* 2

3.3 Maximizing the net present value

In section 3.1 we have shown that the project can be categorized as a max-*npv* problem, which can be solved by the procedure of Vanhoucke et al. (1999). This procedure relies on the intuitive idea that positive cash flows should be scheduled as early as possible while negative cash flows should be scheduled as late as possible within the precedence constraints. Indeed, it is known from financial theory that the time value of money can play an important role in making decisions. As a consequence, a euro received today is more valuable than a euro to be received in some future time period, since the euro today can be invested in order to earn interest.

With this in mind, we propose a schedule in which all activities for which $c_i < 0$ are scheduled as late as possible within the precedence constraints, without delaying the activities with a label 'as soon as possible' (this would lead to a Gantt chart comparable with that of figures 9 and 10 in which all activities are shifted towards the end of the grey bar). We obtain such a schedule with the procedure of Vanhoucke et al. (1999) by assigning a very high positive value for c_i for each grey activity of figure 8. In doing so, we schedule all these grey activities as soon as possible, as required.

This schedule has a net present value of -21,222,684 €, which constitutes an increase of 175,885 €. This means that, by applying the second schedule, a cost saving of 175,885 $e^{-362\alpha}$ = 248,974 € can be made at the end of the project. Despite the gain in the net present value, the proposed schedule is very sensitive to unexpected events during the project. Almost every activity has been scheduled as late as possible, which may cause an increase in the project deadline if one of these activities will be delayed.

In the next section, we describe an approach which combines the advantages of both schedules. This schedule results in a relatively high net present value which does not rapidly run into trouble when something unexpected happens.

3.4 Robust schedule

Since uncertainty is what typifies projects, we propose a new schedule which combines the advantages of both former approaches of sections 3.2 and 3.3. In section 3.2, all activities are scheduled as soon as possible, while the activities of the schedule of section 3.3 are scheduled at their latest finishing times, leaving no slack at all. In our new proposed schedule, we delay the activities with $c_i < 0$ towards their latest finishing times, under the restriction that each activity still needs a fraction of its slack of the earliest start schedule. In doing so, we combine the philosophy of maximizing the net present value with the idea of providing the activities with sufficient slack in order to prevent the violation of the project deadline when something unexpected happens.

More specific, we calculate for each activity the slack by means of the earliest finishing time and latest finishing time schedule (the grey bars as shown in figures 9 and 10). Then, we determine for each activity a *slack-value* which is a fraction of the original slack. Finally, we shift each activity, starting from its earliest finishing time, as far as possible towards its latest finishing, taking the slack-value into account. We repeat this process for different slack-values resulting in different scheduling scenarios.

In the top schedule of figure 11 we display the earliest start schedule of the subproject 'constructing a pump at Zelzate' as described in Table 2 of the appendix. In the bottom schedule of this figure, we have shifted these activities towards their latest finishing time (in order to increase the net present value of activities 40, 43 and 45). Each activity has a slack-value which amounts to 30% or more of the original grey bars of the top schedule. In doing so, the net present value of this subproject increases and the schedule can still handle some unexpected things (such as activity delays, ...).

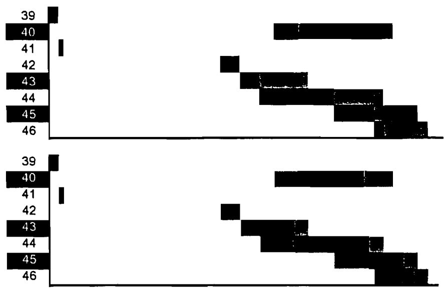

Figure 11. *Earliest start schedule and robust schedule (30% slack value) for the subproject 'constructing a pump at Zelzate' (see Table 2)*

In table 4 we show the finishing times of the activities of the project under different schedules. The column labelled 'earliest finishing time' corresponds to the schedule of section 3.2 (with a minimal *npv*) while the column with label 'latest finishing time' displays the finishing times of schedule 3.3 (with a maximal *npv*). The other columns correspond to schedules with a net present value between these two extremes. Each column has a different number for the slack-value of the activities, ranging from 10% to 90%, in steps of 20%. Remark that an earliest start schedule corresponds to an 100% slack-value while a latest start schedule is identical to a 0% slack-value. The different values of the net present value of each schedule are shown in the second row of the table. The fact that these values are negative does not mean that the project has to be rejected. In the project, only negative cash flows have been considered (from the perspective of the owner of the project). The resulting positive cash flows (once the project will be completed) are known to exceed the total investment costs and, consequently, are not considered in the schedule of the project.

Table 4. *Finishing times of the activities for different schedules of the project (corresponding to different slack-values of an activity)*

Task	Duration	Earliest finishing time	Latest finishing time	Schedule with 90% slack	Schedule with 70% slack	Schedule with 50% slack	Schedule with 30% slack	Schedule with 10% slack
		-21398569,34	-21222684,68	-21385164,04	-21352153,90	-21316158,47	-21281310,40	-21249557,69
1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1
3	7	11	11	11	11	11	11	11
4	130	141	142	141	141	141	141	141
5	1	1	1	1	1	1	1	1
6	8	19	19	19	19	19	19	19
7	16	35	35	35	35	35	35	35
8	50	85	112	87	93	98	103	109
9	40	151	152	151	151	151	151	151
10	4	4	4	4	4	4	4	4
11	10	63	63	63	63	63	63	63
12	8	71	71	71	71	71	71	71
13	8	79	79	79	79	79	79	79
14	40	119	119	119	119	119	119	119
15	12	131	144	132	134	137	140	142
16	52	183	196	184	186	189	192	194
17	10	53	53	53	53	53	53	53
18	10	63	63	63	63	63	63	63
19	10	73	73	73	73	73	73	73

20	45	118	118	118	118	118	118	118
21	26	144	147	144	144	145	146	146
22	15	149	152	149	149	150	151	151
23	26	72	72	72	72	72	72	72
24	26	98	98	98	98	98	98	98
25	26	124	144	126	130	134	138	142
26	10	153	154	153	153	153	153	153
27	26	26	26	26	26	26	26	26
28	70	96	96	96	96	96	96	96
29	52	148	148	148	148	148	148	148
30	4	152	152	152	152	152	152	152
31	4	77	77	77	77	77	77	77
32	26	103	103	103	103	103	103	103
33	26	103	103	103	103	103	103	103
34	12	114	114	114	114	114	114	114
35	26	140	142	140	140	141	141	141
36	10	150	152	150	150	151	151	151
37	2	142	152	143	145	147	149	151
38	2	154	154	154	154	154	154	154
39	4	4	4	4	4	4	4	4
40	10	102	139	105	113	120	127	135
41	1	5	5	5	5	5	5	5
42	8	78	78	78	78	78	78	78
43	8	86	105	87	91	95	99	103
44	30	116	135	117	121	125	129	133
45	15	131	150	132	136	140	144	148
46	4	135	154	136	140	144	148	152
47	8	43	43	43	43	43	43	43
48	15	58	58	58	58	58	58	58
49	5	63	63	63	63	63	63	63
50	26	89	89	89	89	89	89	89
51	10	68	68	68	68	68	68	68
52	18	86	86	86	86	86	86	86
53	5	63	63	63	63	63	63	63
54	1	64	64	64	64	64	64	64
55	75	164	164	164	164	164	164	164
56	4	98	98	98	98	98	98	98
57	10	108	108	108	108	108	108	108
58	8	116	116	116	116	116	116	116
59	30	146	146	146	146	146	146	146
60	20	176	176	176	176	176	176	176
61	8	184	184	184	184	184	184	184
62	8	53	53	53	53	53	53	53
63	15	68	68	68	68	68	68	68
64	5	73	73	73	73	73	73	73
65	26	99	99	99	99	99	99	99
66	10	78	78	78	78	78	78	78
67	18	96	96	96	96	96	96	96
68	5	73	73	73	73	73	73	73
69	1	74	74	74	74	74	74	74
70	52	151	151	151	151	151	151	151
71	4	92	92	92	92	92	92	92
72	10	102	102	102	102	102	102	102
73	8	110	110	110	110	110	110	110
74	30	140	140	140	140	140	140	140
75	10	153	153	153	153	153	153	153
76	4	157	157	157	157	157	157	157
77	0	154	154	154	154	154	154	154
78	4	4	55	9	19	29	39	49

79	10	14	65	19	29	39	49	59
80	8	22	73	27	37	47	57	67
81	26	40	91	45	55	65	75	85
82	10	52	83	55	61	67	73	79
83	52	104	143	107	115	123	131	139
84	10	42	65	44	48	53	58	62
85	0	106	106	106	106	106	106	106
86	6	112	112	112	112	112	112	112
87	8	120	120	120	120	120	120	120
88	26	146	146	146	146	146	146	146
89	26	182	202	184	188	192	196	200
90	8	114	134	116	120	124	128	132
91	40	154	174	156	160	164	168	172
92	2	156	176	158	162	166	170	174
93	2	184	204	186	190	194	198	202
94	8	192	212	194	198	202	206	210
95	0	259	264	259	260	261	262	263
96	4	263	268	263	264	265	266	267
97	10	273	278	273	274	275	276	277
98	26	299	304	299	300	301	302	303
99	26	341	346	341	342	343	344	345
100	10	273	278	273	274	275	276	277
101	40	313	318	313	314	315	316	317
102	2	315	320	315	316	317	318	319
103	4	345	350	345	346	347	348	349
104	0	0	0	0	0	0	0	0
105	20	73	73	73	73	73	73	73
106	14	87	87	87	87	87	87	87
107	10	83	83	83	83	83	83	83
108	26	109	109	109	109	109	109	109
109	10	83	83	83	83	83	83	83
110	26	113	113	113	113	113	113	113
111	156	269	272	269	269	270	271	271
112	20	93	93	93	93	93	93	93
113	10	103	103	103	103	103	103	103
114	8	111	111	111	111	111	111	111
115	52	163	163	163	163	163	163	163
116	52	295	298	295	295	296	297	297
117	26	99	99	99	99	99	99	99
118	26	125	125	125	125	125	125	125
119	26	151	298	165	195	224	253	283
120	20	225	225	225	225	225	225	225
121	12	237	237	237	237	237	237	237
122	40	277	298	279	283	287	291	295
123	12	307	310	307	307	308	309	309
124	15	164	164	164	164	164	164	164
125	40	204	204	204	204	204	204	204
126	15	219	219	219	219	219	219	219
127	26	230	230	230	230	230	230	230
128	16	220	220	220	220	220	220	220
129	52	282	286	282	283	284	284	285
130	40	260	260	260	260	260	260	260
131	26	296	300	296	297	298	298	299
132	26	231	231	231	231	231	231	231
133	26	257	257	257	257	257	257	257
134	26	283	283	283	283	283	283	283
135	10	306	310	306	307	308	308	309
136	52	360	362	360	360	361	361	361
137	0	362	362	362	362	362	362	362

Remark that we have only shifted activities towards the deadline which have slack in figure 8. It is also possible to allow a shift for other activities, such as the activities with label 'as soon as possible'. E.g. shifting the finishing time of activity 61 and 76 to the deadline will not lead to an increase of the project duration. These shifts would lead to a further increase in the net present value.

4 Conclusions

In this paper we have discussed a project scheduling problem at the Vlaamse Maatschappij voor Watervoorziening te Kluizen, Belgium. This project aims at expanding the production capacity of water in East Flanders. It is a very capital-intensive project with a duration of more than 6 years.

Since the net present value lies at the very heart of every budgeting and investment problem, we have shown that the net present value is schedule dependent. In fact, we proposed both an earliest and latest start schedule which each have their own advantages. The former performs worst with respect to the net present value but is less sensitive to changes in the original activity durations. The latter has the opposite effect: it maximizes the net present value but runs into trouble as soon as an activity is delayed. With this in mind, we have proposed some schedules with are combinations of the two. To that purpose, we try to maximize the net present value of the project under the restriction that each activity must have a certain amount of slack, if possible.

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APPENDIX

In this appendix we give a detailed description of the activities of the different steps in the project. Table 1 displays the activities of the first step (activities at the production plant) of subproject 1. This step has a total estimated cost of 7,483,905.51 € = 301,900,000 BEF. The details of the second step (activities outside the production plant) of subproject 1 are shown in table 2 with a total estimated cost of 5,032,238.55 € = 203,000,000 BEF. The list of activities of subproject 2 (increase of the production capacity) is shown in table 3. The total estimated costs amount to 13,262,303.58 € = 535,000,000 BEF for the first alternative (membrane processes) and 11,527,048.90 € = 465,000,000 BEF for the second alternative (air flotation techniques, this second alternative is not treated in this paper since it would lead to the same conclusions with respect to the schedule alternatives of section 3).

Table 1. *Description of the first step of subproject* 1 *consisting of (i) building RWK1, RWK2 and HDZ', (ii) building HSC', (iii) updating existing HDZ to MDZ and (iv) constructing pipes as described in section* 2.1.1 *of the paper*

Task	Task name	Duration (weeks)	Cost (BEF)
New *RWK*1 and *RWK*2 and *HDZ'* (266,900,000 BEF)			
	Architecture		
1	Obtain building license	1	
2	Find contractor (available)	1	
3	Obtain environmental license	7	
4	Execution of work	130	196,900,000
	Equipment		
5	Design (available)	1	
6	Specification	8	
7	Public tender	16	
	Equipment		
8	Fabrication	50	
9	Execution of work	40	70,000,000
***HSC'* (10,000,000 BEF)**			
10	Negotiations with power distribution company	4	3,000,000
	Additional work on cables		
11	Design	10	
12	Specification	8	
13	Request offer	8	
	Realisation		
14	Fabrication	40	
15	Execution of work	12	7,000,000
16	Coming into operation	52	
Updating existing *HDZ* to *MDZ* (10,000,000 BEF)			
17	Design	10	
18	Specification	10	
19	Request offer	10	
	Realisation		
20	Fabrication	45	
21	Execution of work	26	10,000,000
22	Coming into operation	15	
Constructing pipes between installations (15,000,000 BEF)			
23	Design	26	
24	Specification	26	

25	Realisation	26	15,000,000
26	Coming into operation	10	

$FS_{i,j}^{\min} = 0$ except for $FS_{4,9}^{\min} = -30$, $FS_{9,26}^{\min} = -8$, $FS_{21,22}^{\min} = -10$ and $FS_{22,26}^{\min} = -8$

ready times $\rho_i = 0$, except for $\rho_3 = 4$, $\rho_6 = 11$, $\rho_{11} = 53$, $\rho_{17} = 43$, $\rho_{19} = 63$ and $\rho_{23} = 46$.

Table 2. *Description of the second step of subproject* 1 *consisting of (i) constructing pipes from Kluizen to Eeklo, (ii) the water supply to TMVW, (iii) constructing pumps at Zelzate, (iv) constructing pumps and building a water tower at Eeklo and (v) building pumps at Waarschoot as described in section* 2.1.2 *of the paper*

Task	Task name	Duration (weeks)	cost (BEF)
Pipes from Kluizen to Eeklo (170,000,000 BEF)			
27	First draft design	26	
28	Find permission and contractor	70	
29	Construct pipeline	52	170,000,00 0
30	Coming into operation	4	
Water supply to TMVW (1,500,000 BEF)			
31	Design	4	
32	Find permission	26	
33	Connection electricity	26	
	Equipment		
34	Specification equipment	12	
35	Delivery equipment	26	1,000,000
36	Execution	10	
37	Fitting in communication system	2	500,000
38	Coming into operation	2	
Constructing pumps at Zelzate (2,500,000 BEF)			
39	Design for connection electricity	4	
40	Connection electricity	10	400,000
41	Design	1	
42	Specification	8	
43	Request offer	8	1,500,000
44	Delivery	30	
45	Execution	15	600,000
46	Coming into operation	4	
Constructing pumps and building water tower at Eeklo (24,000,000 BEF)			
47	First draft design	8	
48	Design	15	
49	File building license	5	
50	Request building license	26	
51	Specification	10	
52	Public tender	18	
53	File environmental license	5	
54	Notification VLAREM	1	
55	Realisation	75	16,000,000
56	Design	4	
57	Specification	10	
58	Request offer	8	
	Execution		
59	Fabrication	30	
60	Equipment	20	8,000,000
61	Coming into operation	8	
Constructing pumps at Waarschoot (5,000,000 BEF)			
62	First draft design	8	
63	Design	15	
64	File constructing license	5	
65	Request constructing license	26	

66	Specification	10	
67	Public tender	18	
68	File environmental license	5	
69	Notification VLAREM	1	
70	Realisation	52	
71	Design	4	
72	Specification	10	
73	Request offer	8	
	Execution		
74	Fabrication	30	
75	Equipment	10	5,000,000
76	Coming into operation	4	

$FS_{i,j}^{\min} = 0$ except for $FS_{27,31}^{\min} = 26$, $FS_{40,45}^{\min} = -4$, $FS_{48,56}^{\min} = 36$, $FS_{55,60}^{\min} = -8$, $FS_{63,71}^{\min} = 20$ and $FS_{70,75}^{\min} = -8$. Moreover, between 47 and 62, $SS^{\min}$=10 so $FS^{\min}$=2

ready times $\rho_i = 0$, except for $\rho_{31} = 73$, $\rho_{34} = 102$, $\rho_{37} = 44$, $\rho_{40} = 92$, $\rho_{42} = 70$ and $\rho_{47} = 35$.

Table 3. *Description of subproject* 2 *consisting of building carbon filters in (i) phase* 1 and *(ii) phase* 2, *(iii) the treatment of water and (iv) the treatment of waste as described in section* 2.2 *of the paper*

Task	Task name	Duration (weeks)		cost (BEF)	
Carbon filters (*AKF'*), phase 1 (90,000,000 BEF)					
78	First draft design AKF (2 alternatives)	4			
79	Design AKF	10			
80	Specification AKF	8			
81	Building license procedure	26		500,000	
82	Public tender	10		25,000,000	
83	Execution building reservoir for *AKF*	52			
84	Design carbon filter	10			
85	Determine number of filters	0			
86	Specification	6			
87	Request offer	8			
	Equipment *AKF*				
88	Fabrication materials	26			
89	Execution of work	26		20,000,000	
90	Request offer	8			
	Carbon filters				
91	Construction filters	40			
92	Delivery filters	2		35,000,000	
93	Delivery Carbon	2		5,000,000	
94	Coming into operation *AKF*	8			
Carbon filters (*AKF'*), phase 2 (100,000,000 BEF)					
95	Determine number of carbon filters	0			
96	Specification	4			
97	Request offer	10			
	Equipment *AKF*				
98	Fabrication materials	26			
99	Execution of work	26		10,000,000	
100	Request offer	10			
	Carbon filters				
101	Construction filters	40			
102	Delivery filters	2		90,000,000	
103	Coming into operation *AKF*	4			
Water treatment (membrane or air flotation) (305,000,000 BEF for alternative 1 and 235,000,000 BEF for alternative 2)					
		Alt. 1	Alt. 2	Alt. 1	Alt. 2
104	First draft design flotation filtering	0.2	26		

105	First draft design and specification of architecture	20	52		
106	Public tender	14	18		
107	Preparation building license	10	26		
108	Request building license	26	26		
109	Preparation environmental license	10	26		
110	Request environmental license	26	26		
111	Realisation architecture for flotation or membrane technique	156	104	200,000,000	40,000,000
112	Design for flotation/membrane technique	20	26		
113	Specification	10	10		
114	Request offer	8	10		
	Equipment for flotation/membrane technique				
115	Fabrication	52	52		
116	Execution of work	52	52	70,000,000	150,000,000
	Connection installations				
117	Design	26	26		
118	Specification	26	26		
119	Realisation	26	26	20,000,000	20,000,000
	Automation				
120	Design	20	26		
121	Request offer automation	12	26		
122	Realisation equipment	40	52	15,000,000	15,000,000
123	Coming into operation (flotation or membrane technique)	12	12		
Waste treatment (40,000,000 BEF)					
124	First draft design	15			
125	Design	40			
126	Specification	15			
127	Obtain environmental and building license	26			
128	Design and specification	16			
129	Realisation architecture	52		20,000,000	
	Realisation				
130	Fabrication	40			
131	Execution of work	26		20,000,000	
	Connect installations				
132	Design	26			
133	Specification	26			
134	Realisation	26			
135	Coming into operation (installation)	10			
136	Coming into operation (extra production)	52			

$FS_{i,j}^{\min} = 0$ except for $FS_{83,89}^{\min} = -10$, $FS_{94,95}^{\min} = 52$, $FS_{129,131}^{\min} = -12$ and $FS_{103,136}^{\min} = -40$

ready times $\rho_i = 0$, except for $\rho_{82} = 42$, $\rho_{84} = 32$, $\rho_{85} = 106$, $\rho_{95} = 259$ and $\rho_{136} = 308$.

Alternative 1

$FS_{i,j}^{\min} = 0$ except for $FS_{111,116}^{\min} = -26$.

ready times $\rho_i = 0$, except for $\rho_{105} = 53$, $\rho_{106} = 70$, $\rho_{120} = 205$, $\rho_{124} = 149$ and $\rho_{132} = 205$.

Alternative 2

similar to alternative 1